Experimental study of heat and mass transfer in convective air flows of moist air with droplet condensation as a function of surface roughness and wetting properties

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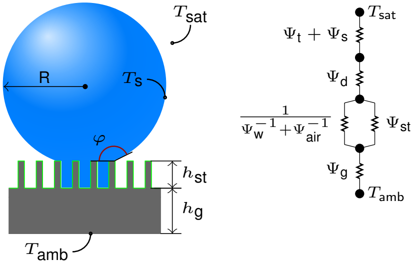
DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Motivation

Droplet condensation on surfaces: a phenomenon in technical applications and our everyday life

impact of surface properties on fogging and defogging of windshields

Heat transport on a rough surface with droplet condensation



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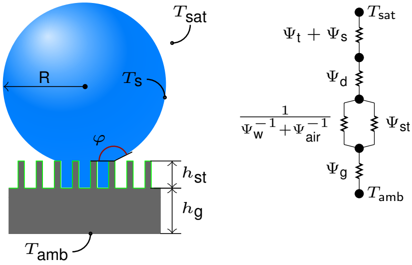

thermal resistance : $\Psi_t = {}^{2\,T_s\,\sigma}\!/\!_{R\,h_v\,\varrho_v\,\dot{Q}}$

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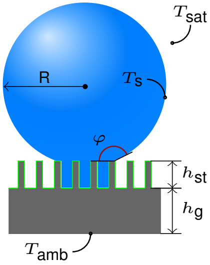

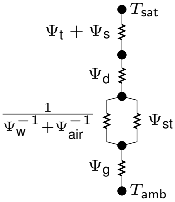

thermal resistance : $\Psi_t = {}^{2\, T_s\, \sigma}/_{R\, h_v\, \varrho_v\, \dot{Q}}$

droplet surface : $\Psi_s = {}^{1}/_{\alpha_s 2\, \pi\, R^2\, (1 - \cos(\varphi))}$

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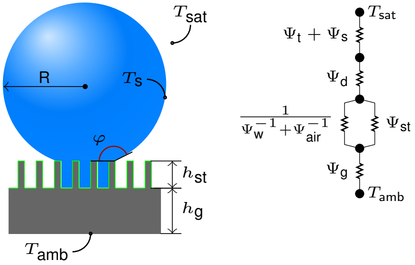

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droplet : $\Psi_{\text{d}} = {}^{\Theta}/_{4\pi R \lambda_{\text{w}} \sin(\varphi)}$

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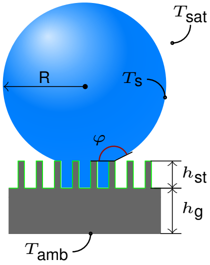

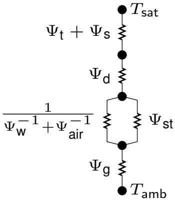

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surface structure : $\left({}^{1}/_{\Psi_{st}} + {}^{1}/_{\Psi_w} + {}^{1}/_{\Psi_{air}}\right)^{-1} = {}^{h_{st}}/_{\pi R^2 \lambda_{st} \sin^2(\varphi)(A_{air}\,\lambda_{air} + (1-A_{air})\lambda_w)}$

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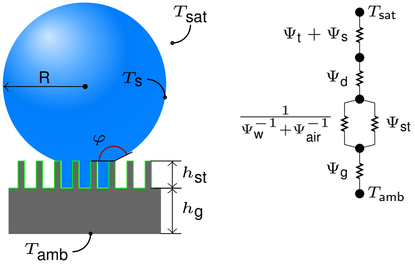

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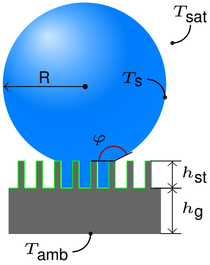
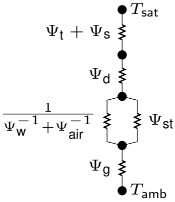
glass pane : $\Psi_{\mathsf{g}} = {}^{h_{\mathsf{g}}}/_{\pi R^2 \sin^2(\varphi)\lambda_{\mathsf{g}}}$

Heat transport on a rough surface with droplet condensation





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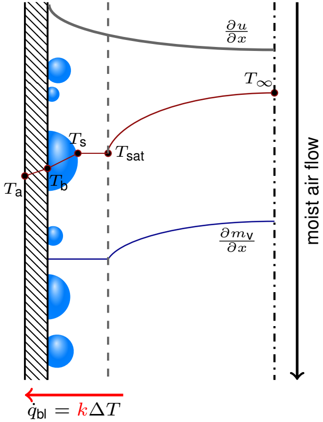
glass pane : $\Psi_g = {}^{h_g}/_{\pi R^2 \sin^2(\varphi)\lambda_g}$

total heat transmittance : $k = \left(\Psi_{\mathbf{t}} + \Psi_{\mathbf{s}} + \Psi_{\mathbf{d}} + \left(\frac{1}{\Psi_{\mathbf{st}}} + \frac{1}{\Psi_{\mathbf{w}}} + \frac{1}{\Psi_{\mathbf{air}}}\right)^{-1} + \Psi_{\mathbf{g}}\right)^{-1}$

Heat and mass transfer in forced convection with phase transition

MODEL EQUATIONS



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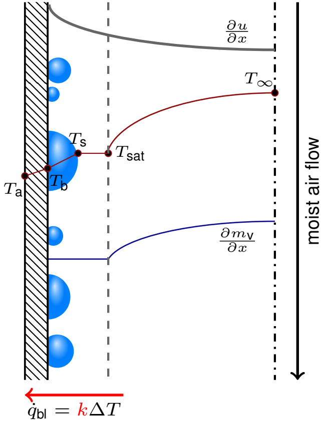


MODEL EQUATIONS

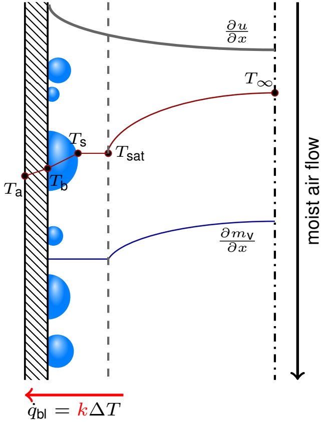
$$\text{continuity}: \frac{D\varrho}{Dt} = -\varrho\nabla\vec{u}$$

$$\text{fluid motion}: \varrho\frac{D\vec{u}}{Dt} = -\nabla p + \eta\nabla^2\vec{u} + \vec{F}_b$$

$$\text{heat}: \varrho\, c_p\frac{DT}{Dt} = \lambda\nabla^2 T + \beta T\frac{Dp}{Dt} + H_v\frac{D\varrho_v}{Dt}$$

$$\text{diffusion}: \frac{D\varrho_v}{Dt} = D\,\nabla^2\varrho_v$$

Heat and mass transfer in forced convection with phase transition



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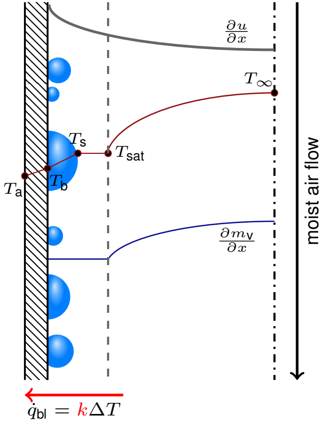
$$\text{diffusion}: \frac{\mathrm{D}\varrho_v}{\mathrm{D}t} = D\,\nabla^2\varrho_v$$

$$\nabla'\vec{u}' = 0$$

$$\vec{u}'\nabla'\vec{u}' = -\nabla' p' + \frac{1}{\mathcal{R}e}\nabla'^2\vec{u}' + \frac{1}{\mathcal{F}r^2}\vec{e}_z$$

$$\nabla' T' = \frac{1}{\mathcal{R}e\,\mathcal{P}r}\nabla'^2 T' + \frac{1}{\mathcal{J}a\,\mathcal{S}h}\nabla'^2\varrho_v'$$

Heat and mass transfer in forced convection with phase transition



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$$\nabla' T' = \frac{1}{\mathcal{Re}\,\mathcal{Pr}}\nabla'^2 T' + \frac{1}{\mathcal{Ja}\,\mathcal{Sh}}\nabla'^2\varrho_v'$$

SURFACE PROPERTIES

$$\text{contact angle}: \cos(\Theta) = \frac{\sigma_{sg} - \sigma_{ls}}{\sigma_{lg}}$$

$$\text{roughness}: R_z = \frac{\left|\sum_{i=1}^N Y_{p_i}\right| + \left|\sum_{i=1}^N Y_{v_i}\right|}{N}$$

Gap wind tunnel / air supply system

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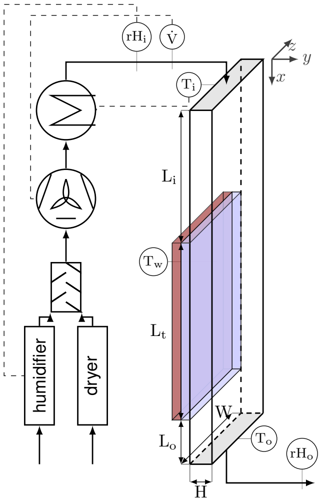

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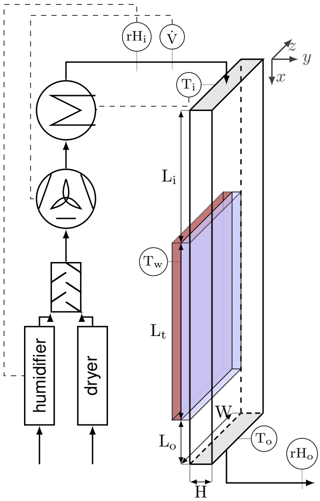

DIMENSIONS

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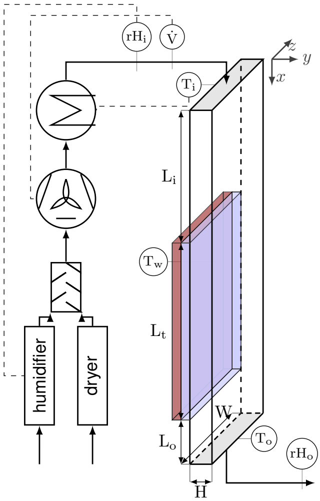

DIMENSIONS

height : $H = 20$ mm ○ width : $W = 529$ mm

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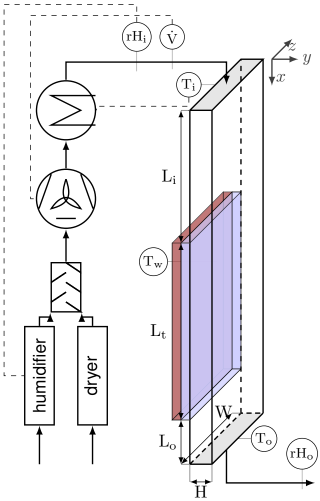

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length inflow section : $L_{\text{i}} = 1500$ mm

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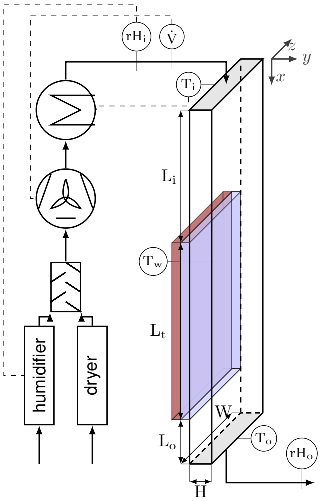

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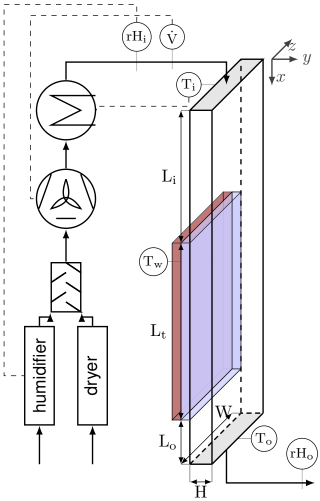

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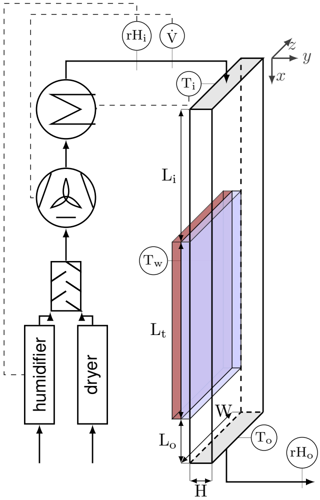

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BOUNDARY CONDITIONS

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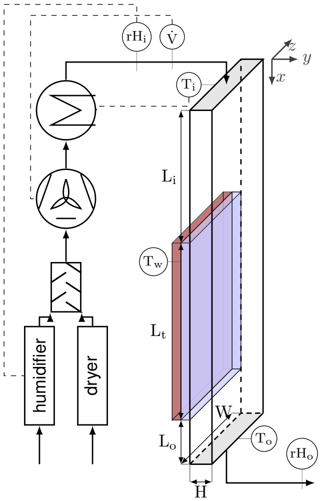

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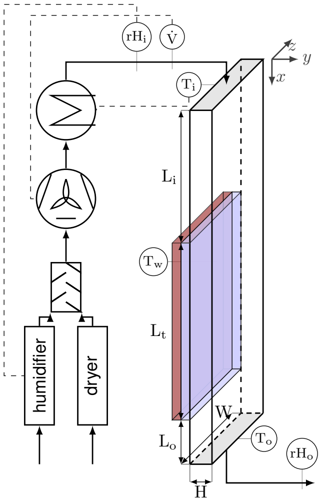
BOUNDARY CONDITIONS

$$T_\mathrm{w} = 12.5^oC + 7.5^oC \cdot \cos\left(2\pi \frac{t+900\,\mathrm{s}}{\tau}\right),\ \tau = 3600\ \mathrm{s}$$

$$T_\mathrm{sw} = T_\mathrm{a}$$

Θ_i [^{o}C]	T_i [^{o}C]	U [m/s]	$\mathcal{R}e$ [-]
12.5	32.5	1.0	2200
12.5	32.5	2.0	4500
13.5	32.5	2.9	6600

Gap wind tunnel / air supply system



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SURFACE PROPERTIES GLASS PANE

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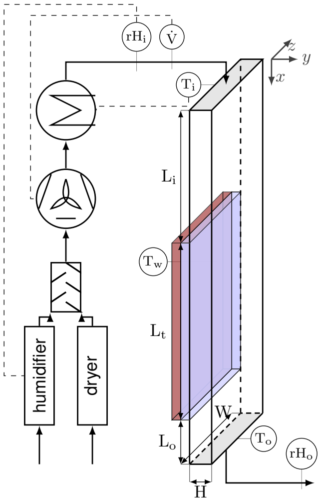

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surface	R_{z} [nm]	$\epsilon = R_{\mathrm{z}}/H$ [-]	contact angle $\overline{\varphi}$ [^{o}]
hydrophobic	≈ 60	0.3×10^{-5}	 101 ± 2
hydrophilic	≈ 60	0.3×10^{-5}	 33 ± 5
polyester I	230	1.15×10^{-5}	 72 ± 2
polyester II	650	3.25×10^{-5}	 67 ± 3

Characteristic numbers

Cha. number	Definition	physical Interpretation
Reynolds	$\mathcal{R}e = \frac{U_{\text{in}}\, d_{\text{h}}\, \varrho}{\eta}$	inertial forces to viscous forces
Contact angle	$\cos(\varphi) = \frac{\sigma_S - \sigma_{LS}}{\sigma_L}$	surface tensions
Roughness	$\epsilon = \frac{R_{\text{z}}}{H} = \frac{1/N \left\| \sum_{i=1}^{N} Y_{\text{p}_i} \right\| + \left\| \sum_{i=1}^{N} Y_{\text{v}_i} \right\|}{L}$	ratio of R_{z}* to gap length
Prandtl	$\mathcal{P}r = \frac{\eta c_{\text{p}}}{\lambda_{\text{air}}}$	momentum to thermal diffusivity
Froude	$\mathcal{F}r = \frac{U_{\text{in}}}{\sqrt{\Delta\varrho/\varrho\, g\, L}}$	inertia to gravitational forces
Jakobs	$\mathcal{J}a = \frac{(T_\infty - T_{\text{w}})\, c_{\text{p}}}{h_{\text{v}}}$	sensible to latent heat
Sherwood	$\mathcal{S}h = \frac{\dot{M}_{\text{v}}\, H}{A\, D_{\text{v}} \Delta\varrho_{\text{v}}}$	mass transfer to diffusion
Nusselt	$\mathcal{N}u = \frac{k\, L}{\lambda_{\text{air}}}$	convection to heat conductance

* DIN EN ISO 428

Calculation of system temperature and heat transmittance

$$\frac{\mathrm{d}T}{\mathrm{d}x} = \frac{1}{c_{\mathrm{p}}^{\mathrm{air}}\,\dot{M}_{\mathrm{air}}}\left[\underbrace{W\,k\,(T(x) - T_{\mathrm{w}})}_{\dot{Q}_{\mathrm{g}}} + \underbrace{(2\,H + W)\,k_{\mathrm{sw}}(T(x) - T_{\mathrm{a}})}_{\dot{Q}_{\mathrm{sw}}} + \underbrace{W\,\frac{\dot{M}_{\mathrm{v}}(x)}{A}\,H_{\mathrm{v}}}_{\dot{Q}_{\mathrm{pt}}}\right]$$

initialise T_{m}

$$\dot{Q}_{\mathrm{sw}} = k_{\mathrm{sw}}\,(2H + B)\,L\,(T_{\mathrm{m}} - T_{\mathrm{sw}})$$

$$k_g' = \frac{(\dot{Q}_{\mathrm{t}} - \dot{Q}_{\mathrm{pt}} - \dot{Q}_{\mathrm{sw}})}{L\,W\,(T_{\mathrm{m}} - T_{\mathrm{w}})}$$

$$|T(L) - T_{\mathrm{o}}| \leq \epsilon$$

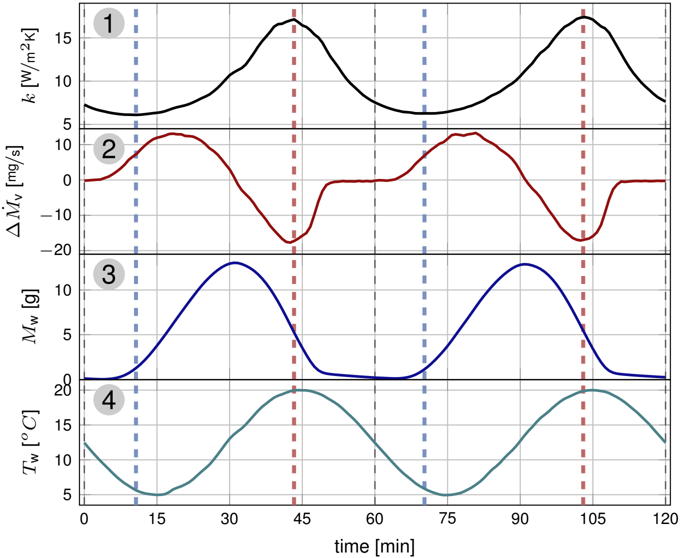
False

$$T_{\mathrm{o}}' > T_{\mathrm{o}} \rightarrow T_{\mathrm{m}} = \frac{1}{L}\int T(x)\mathrm{d}x - \delta$$
$$T_{\mathrm{o}}' < T_{\mathrm{o}} \rightarrow T_{\mathrm{m}} = \frac{1}{L}\int T(x)\mathrm{d}x + \delta$$

True

$$T_{\mathrm{m}} = \frac{1}{L}\int T(x)\mathrm{d}x$$
$$k = \frac{(\dot{Q}_{\mathrm{T}} - \dot{Q}_{\mathrm{pt}} - \dot{Q}_{\mathrm{sw}})}{L\,W\,(T_{\mathrm{m}} - T_{\mathrm{w}})}$$

Heat transmittance and phase transition



$$\mathcal{R}e = 2200$$

$$\epsilon = 1.15 \times 10^{-5}$$

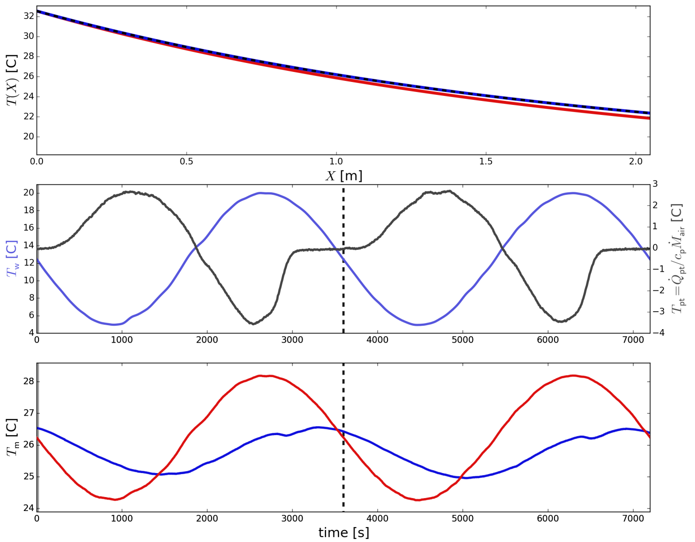
$$\varphi = 72$$

$$T_{in} = 32^o\text{C}$$

$$\Theta_i = 12.5^o\text{C}$$

$$\text{total time} = 7200\text{s}$$

System temperatures



$\mathcal{R}e = 2200$

$\epsilon = 1.15 \times 10^{-5}$

$\varphi = 72$

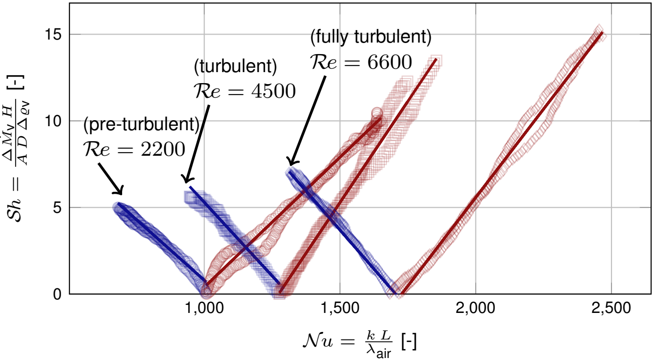
$T_i = 32^o$C

$\Theta_i = 12.5^o$C

total time = 7200s

- phase change
- no phase change

$\mathcal{S}h$-$\mathcal{N}u$-relation as a function of $\mathcal{R}e$



• condensation
• evaporation

$\epsilon = 1.15 \times 10^{-5}$

$\varphi = 72^o$

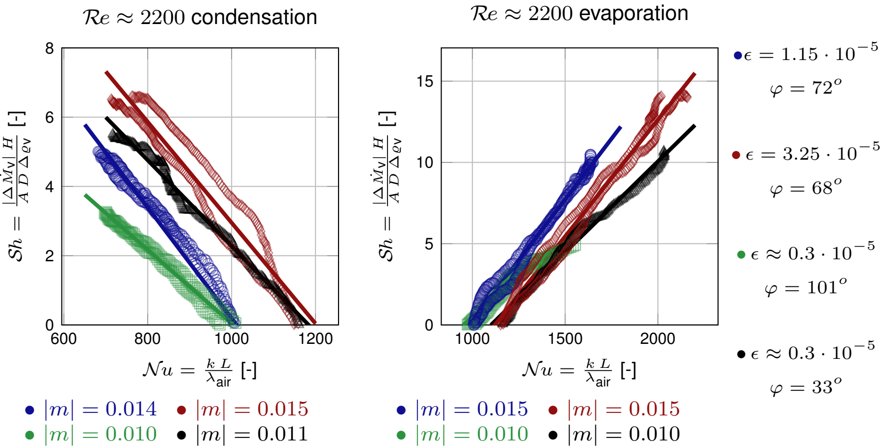
$\mathcal{R}e = 2200$
$|m_\text{c}| = 0.014, |m_\text{e}| = 0.015$

$\mathcal{R}e = 4500$
$|m_\text{c}| = 0.017, |m_\text{e}| = 0.022$

$\mathcal{R}e = 6600$
$|m_\text{c}| = 0.018, |m_\text{e}| = 0.021$

- linear relation $\mathcal{S}h = m\,\mathcal{N}u + C$
- $\mathcal{R}e = 2200$ similar slopes $|m|$ for condensation and evaporation
- different slopes $|m|$ for condensation and evaporation in case of turbulent flow
- higher $|m|$ for turbulent indicates higher mass transfer due to phase transition in ratio to diffusive mass transfer

Sh-Nu-relation for different surfaces



- similar slopes $|m|$ for condensation and evaporation
- higher slopes for rough surface and lower slopes for the smoother surfaces
- slope $|m|$ increases in case of higher surface roughness ϵ

Summary

- definition and characterisation of mass and heat transport in forced convective air flow with phase transition
- introduction of the test facility and the air supply system
- analysing method to calculate the mean heat transmission coefficient between the cooling plate and the fluid
- linear relation $\mathcal{S}h = m\,\mathcal{N}u + C$ for the present parameter space
- higher surface roughness leads to an increased vapour mass transfer due to phase transition in ratio to the diffusive mass transfer
- similar slopes for condensation and evaporation for $\mathcal{R}e = 2200$
- different slopes for condensation and evaporation for turbulent flow
- increased slopes in case of higher $\mathcal{R}e$ indicating better mixing due to turbulence

THANK YOU FOR YOUR ATTENTION!

ACKNOWLEDGEMENT

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https://www.vda.de/de/services/Publikationen/fat-schriftenreihe-307.html